STUDY OF OCCUPATIONAL MAGNETIC-FIELD PERSONAL EXPOSURES OF NON-FLYING AIRLINE EMPLOYEES

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NOTICE

EXECUTIVE SUMMARY

This study characterized the occupational exposures to magnetic fields of non-flying workers employed by a major airline company. Ninety-seven volunteer workers, holding 15 different job titles, volunteered to wear Emdex II magnetic-field meters at a waist location for one work shift. These meters recorded the broadband (40–800 Hz) and harmonic (100–800 Hz) magnetic fields sampled every 3 s. Using the resulting data, the following eight exposure metrics were calculated:

- Time-weighted-average broadband personal magnetic-field exposure
- Time-weighted-average harmonic personal magnetic-field exposure
- 90^{th} percentile broadband personal magnetic-field exposure
- Fraction of time during work shift broadband exposure > 2 mG
- Fraction of time during work shift broadband exposure > 5 mG
- Fraction of time during work shift broadband exposure > 10 mG
- Temporal broadband magnetic-field variability using the *RCM* metric
- Temporal broadband magnetic-field variability using the *RCM** metric

The geometric means of the time-weighted-average (TWA) broadband magnetic-field exposures of workers with the selected job titles varied from a low of 0.44 mG for Lead Reservation Agents to a high of 1.92 mG for Maintenance Supervisors. Other job titles with TWA broadband exposures above 1 mG were Concourse Agents (1.31 mG), Lead Concourse Agents (1.22 mG), and Mechanics (1.10 mG).

Four different metrics were used to capture peak magnetic-field exposure. The geometric means of the 90^{th} percentile exposure ranged from 0.71 mG for Ticket Counter Agents and Lead Reservation Agents to 5.32 mG for Maintenance Supervisors. The fractions of time during work shifts that broadband magnetic-field exposure exceeded 2 mG varied from 0.01 for Ticket Counter Agents and Lead Reservation Agents to 0.16 for Maintenance Supervisors. The pattern of exposure was similar when the fractions of measurements > 5 mG and > 10 mG were used as metrics, except all jobs were characterized by progressively smaller values.

Jobs that involved work inside or near airplanes conveyed some exposure to 400-Hz magnetic fields. These jobs included Ramp Agents, Lead Ramp Agents, Fleet Agents, Lead Fleet Agents, Mechanics, and Maintenance Supervisors.

Temporal variability of the broadband exposure magnetic field was assessed using the *RCM* and *RCM** metrics. The *RCM* metric varied from 0.24 mG for Ticket Counter Agents to 1.32 mG for Supervisors of Ground Operations. There was little relation between the *RCM* and *RCM** values for job titles. Thus, the two largest values of *RCM** corresponded to the two job titles with the largest (Supervisors of Ground Operations) and smallest (Lead Reservations Agents) values of *RCM*.

The average TWA broadband personal exposure to magnetic fields for non-flying workers employed in a major airline company was 1.24 mG, a value which is only slightly elevated relative to the typical U.S. residence. Based on our measurements, the predicted numbers of employees with TWA broadband personal exposures > 2 mG and > 5 mG are about 131 and 41, respectively. These numbers do not seem sufficient to support an epidemiological study with the goal of detecting associations between TWA broadband exposure and human disease.

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I. INTRODUCTION

I.1. Description of Study

This report presents the results of a project to characterize the exposures of non-flying personnel employed by a major airline company in the United States. To accomplish this goal, 97 Seattle-based employees of Alaska Airlines wore recording magnetic-field meters during single work shifts. These individuals were employed in the Ramp and Fleet Services, Customer Services, Reservations, and Maintenance Departments and were selected to provide exposure data for those jobs held by the largest number of employees in these departments.

The remainder of this chapter provides background information readers may find helpful in understanding the rest of the report. Chapter II describes our experimental procedures and the equipment we used for the study. Chapter III presents the results of the study, and Chapter IV provides a discussion of these results.

I.2. Electric and Magnetic Fields

Scientists have identified four fundamental forces in nature: the force of gravity, the electromagnetic force, the weak nuclear force, and the strong nuclear force. The two that we most often experience in our everyday lives are the forces of gravity and electromagnetism. This report is concerned with the latter force—electromagnetism.

A characteristic of the fundamental particles that make up matter is their electric charge. Electromagnetic forces act between electrically charged particles and, among other things, bind together the constituents of atoms and molecules (i.e., protons, neutrons, and electrons). The electromagnetic forces between particles are "carried" by two types of fields, the electric field and the magnetic field. Electric fields are always produced by electric charge, but magnetic fields are produced *only* by electric charges in *motion.* An electrically charged particle placed in electric and magnetic fields will experience an electric force and, *if* it is moving, a magnetic force.

The basic element of an electric power system, such as the one that powers our homes, work places and, indeed, virtually all parts of our society, is the controlled application of electric and magnetic fields to electric currents. Since an electric current is the *movement* of electric charge, usually in a wire or other electrical conductor, the use of electric power inevitably involves the generation of electric and magnetic fields.

The electric field produced by an electric power system is directly related to the system voltage, which is measured in volts (abbreviated V). Electric fields have the units of volts per meter, or V/m. The magnitude of a current in a wire is defined to be the amount of electric charge that passes through it in one second. The unit of current is the ampere (abbreviated A).

A force has two characteristics: its strength and the direction in which it is acting. For example, the strength of the force of gravity depends on the mass of an object and its direction is always downwards. Since electric and magnetic fields are related to forces, it is not surprising that they also are each characterized by both a strength and direction. Measurement of three quantities, the x, y, and z components, is required to completely characterize a vector at any instant of time.

In many situations, including most involving our electric power system, the flow of electric current in a wire periodically and regularly shifts from one direction to the opposite and back. Currents with this character are called alternating currents (abbreviated ac). Magnetic fields produced by such currents have continually varying magnitudes and directions. The number of times in one second that a current or field goes through one complete cycle, that is from one direction to the other and back, is called the quantity's frequency and is expressed using the unit hertz, abbreviated Hz.

Typical electric-field strengths measured in residences are in the range 0.1 - 10 V/m (Caola et al., 1983; Barnes et al., 1989). Electric fields at ground level directly under the conductors of a very high voltage transmission line (e.g., 500,000 volt transmission line) range from about 3,000 through 10,000 V/m. In the United States, magnetic fields with frequencies ranging from static through a few thousand hertz are generally specified in units of milligauss, abbreviated mG. The earth's static magnetic field is about 500 mG, although this value is easily altered by structures that utilize iron, steel, or other ferromagnetic materials. Typical magnetic fields in residences measured at one point in time in the centers of rooms (hence, not near home appliances) range from about 0.1 through 10 mG (Zaffanella, 1993). Under heavily-loaded transmission lines (i.e., transmission lines carrying large amounts of electric power and, thus, large currents), magnetic fields typically range from about 10 to 100 mG; in a few situations, even larger ground-level magnetic fields can be measured near power lines.

I.3. Physical Interaction of Electric and Magnetic Fields With Living Tissues

Electric and magnetic fields are produced by charged particles (particles in motion for magnetic fields) and exert forces on other charged particles (again, charged particles in motion for magnetic fields). The human body is made up of a vast number of charged particles. All of these particles will experience electric and magnetic (if they are moving) forces when placed in electric and magnetic fields. It is at least conceivable that these forces could have some effect on the functioning of living tissues.

The character of the interaction of living tissues with electric and magnetic fields depends strongly on frequency. For example, the frequency used in a microwave oven has been selected so that electric and magnetic fields produced in the unit can rapidly raise the temperature of foods by 100°F or more. The situation at 60 Hz is very different. At this low frequency, only extremely small amounts of energy can be delivered to living tissues by alternating electric and magnetic fields of even the very highest strengths that can be produced in air. Indeed, the amount of energy that can be delivered by these fields is normally much less than the amounts of energy involved with the normal thermal and physiological processes that occur naturally in all living tissues.

At 60-Hz, electric fields applied to the body through air are almost completely shielded by the surface of the body. In most parts of the body, the electric field induced inside by an externally applied electric field is reduced by at least a factor of one million. (That is, the electric field inside the body is at least one million times smaller than the field outside it.) Similar, although not nearly as strong, shielding is produced by the exterior walls of a home or commercial building (Caola et al., 1984). Sixty-hertz magnetic fields, on the other hand, are able to penetrate living tissues (and the walls of most buildings) virtually without attenuation. Magnetic fields can induce current flow inside a living body. The sizes of these currents appear to be generally small compared to the natural currents that occur in tissues (Weaver and Astumian, 1990).

The situation is quite different if some part of the body comes into direct physical contact with an energized conductor (i.e., a conductor with a voltage applied to it). In this case, there is no need to couple electric fields into the body through an intervening length of air. Rather, the fields can be coupled directly into the body through conductive contact. As is certainly well known to the reader, this coupling can be very dangerous, especially if the voltage is much above 100 V. It takes a only a very small current (a small fraction of 1 ampere) passing in the neighborhood of the heart to interfere with its operation. If this interference is sufficiently strong, death may result.

I.4. Concern About Health Effects Resulting From Magnetic-Field Exposure

To date, studies of magnetic fields and adverse human health effects have tended to concentrate on cancer, most frequently, brain cancer, various types of leukemia, and male and female breast cancer. (A comprehensive recent review of magnetic-field health effects research is given in NIEHS, 1998.) Other diseases have been studied, with less intensity, and there are published reports that, for example, link magnetic-field exposure with amyotrophic lateral sclerosis (Davanipour and Sobel, 1997) and Alzheimer's disease (Sobel et al., 1995, 1996).

The first suggestion that magnetic-field exposure might be a risk factor for human disease was made by Wertheimer and Leeper (1979) who found that children who lived in homes near certain types of configurations of external electric wiring were at a higher risk of developing leukemia. Similar finding were subsequently obtained by Savitz et al. (1988) and London et al. (1991). Three recent studies (Linet et al., 1997; McBride et al., 1999; Green et al., 1999a, 1999b), however, failed to find any link between wiring configuration and childhood leukemia, in contrast to the three previously mentioned studies. One of these studies (Linet et al., 1997) did find some evidence of an association between measured magnetic fields and disease and another (Green et al., 1999a) reported a fairly robust association between leukemia and measured personal exposures of children to magnetic fields. Similar associations with measured or calculated magnetic fields have been reported in other studies (e.g., Feychting and Ahlbom, 1993; Olsen et al., 1993).

The strength of the median and average magnetic fields in U.S. residences are about 0.6 and 0.9 mG, respectively (Zaffanella, 1993). Median and average magnetic fields experienced by individuals while at work in the US are about 1.0 and 1.8 mG, respectively (Zaffanella, 1998). Since some occupations involve work near equipment that use or convey large amounts of electric power, it may be that workers in these occupations are exposed to magnetic fields considerably larger than those found in residences or in most occupational environments. Thus, studies in occupational environments might be a more fruitful area to examine for possible human health effects of magnetic field exposure. And, indeed, a number of occupational studies have been performed (a review of occupational studies is given in NIEHS, 1998), some of which have reported increased health risks in occupations what were thought to involved larger exposures to magnetic fields.

The majority of the occupational studies conducted to date have focused on job titles loosely classed as "electrical workers." The first of these reports (Milham, 1982) focused on mortality rates in Washington State and found that electrical workers had a higher risk of leukemia compared to workers in other occupations. Since this report, scientists have used occupational classifications as a surrogate for exposure assessment in many epidemiological studies. Recent studies have incorporated actual magnetic-field measurements as part of their exposure assessment protocol. Of these latter studies, several have found associations between occupational exposure measurements and increased risk for certain cancers (Savitz and Loomis, 1995; Theriault et al., 1994; Floderus et al., 1993, London et al., 1994) and one has found no association between exposure and cancer (Sahl et al., 1993).

Finally, attention has been given to the possible association between breast cancer and magnetic field exposure. This interest was initially stimulated by the discovery by Stevens (1987) of a possible mechanism linking this exposure to breast cancer. There are some occupational epidemiological data (see NIEHS, 1998 for a summary) that suggest a possible link between male and female breast cancer and magnetic-field exposure.

It is difficult to know what to conclude on the basis on currently published scientific literature studying whether electric and magnetic fields, with frequencies in the extremely low-frequency range (ELF, 30-3000 Hz) affect human health. The National Institute of Environmental Health Sciences recently conducted a very lengthy assessment of this literature and concluded that (NIEHS, 1999):

> "The scientific evidence suggesting that ELF-EMF exposures pose any health risk is weak. The strongest evidence for health effects comes from associations observed in human populations with two forms of cancer: childhood leukemia and chronic lymphocytic leukemia in occupationally exposed adults. While the support from individual studies is weak, the epidemiological studies demonstrate, for some methods of measuring exposure, a fairly consistent pattern of a small, increased risk with increasing exposure that is somewhat weaker for chronic lymphocytic leukemia than for childhood leukemia. In contrast, the mechanistic studies and animal toxicology literature fail to demonstrate any consistent pattern across studies although sporadic findings of biological effects (including

increased cancers in animals) have been reported. No indication of increased leukemias in experimental animals has been observed."

I.5. Measurements in Other Electrically Powered Transportation Systems

The Federal Railway Administration (FRA) of the U.S. Department of Transportation has studied the electric and magnetic fields produced by several different types of conventional and advanced electrically powered ground transportation systems. The results of this study are presented in several reports System (Dietrich et al., 1993a, 1993b, 1999); data collected in or prior to 1993 are summarized in a separate report (Dietrich et al., 1993c). These studies have included the Massachusetts Bay Transportation Authority (MBTA) and the Washington DC Metropolitan Area Transit Authority Metrorail.

In addition, two studies have been completed of the magnetic fields to which employees of a organization that operates a electrically powered trolley system are exposed (Kaune, 1994, 1999). The first of these studies (Kaune, 1994) concentrated on surveys of the magnetic fields in the work areas of various selected employees. The second study (Kaune, 1999) extended this work by having 104 workers wear personal exposure magnetic-field meters during their work shifts. The study found that the population exposure to magnetic fields, averaged over work shifts, was 1.5 mG.

We are not aware of any published literature concerned with the exposures of the employees of airline companies to magnetic fields.

II. MATERIALS AND METHODS

II.1. Sampling Plan

This study examined most workers employed by Alaska Airlines who worked in the vicinity of the Seattle-Tacoma Airport and whose jobs did not involve work on aircraft while in flight. During initial discussions with the company, it was decided to include workers in the following departments of the airline: Ramp and Fleet Services, Customer Services, Reservations, and Maintenance. Personnel in Ramp and Fleet Services load baggage, clean aircraft prior to passenger boarding, and load meals and other supplies into aircraft while they are on the ramp. The Customer Services department includes agents that deal with passengers and their baggage while they are in airports. The Reservations department includes staff who sell tickets to passengers by telephone. The Maintenance Department includes personnel who perform aircraft maintenance.

The corporate headquarters of Alaska Airlines is also located close to the Seattle-Tacoma Airport. We did not include this group in the study because there was nothing about the working environment in the facility they inhabit that distinguished it from the corporate headquarters of other industries.

The total worker population from which we drew our sample thus consisted of 1315 workers holding 41 job titles. A list of the job titles and numbers of people employed with each title are given in Table 1.

Resource and time constraints made it impossible to measure the exposure of every worker, or even of sample of workers, employed in *all* of the jobs listed in Table 1. Instead, a sampling plan was developed in order to apportion the number of workers to be sampled among the total population. Suppose that we have J job titles under study, and let the total number of workers in the j^{th} job title be W_j. The total number of workers in all job titles is W, where $W = W_1 + W_2 + \ldots + W_J$. Suppose that we have the resources to make a total of S measurements and want to know how to distribute these measurements between the various job titles under study.

Now assume that S_j workers are sampled from job title j ($S_j \leq W_j$). Let the measured exposure for the k^{th} sampled worker in this job title be X_{jk}. Then, the best estimate, X_j, of true exposure of this job title is obtaining by averaging the results of the sample, that is,

Table 1 Job titles of non-flying personnel employed in Alaska Airlines departments included in the study.

Department	Job Title	# Workers
Fleet & Ramp Services	Fleet Service Agent	101
Fleet & Ramp Services	Lead Fleet Service Agent	19
Fleet & Ramp Services	Fleet Service Trainer	1
Fleet & Ramp Services	Ramp Service Agent	316
Fleet & Ramp Services	Lead Ramp Service Agent	49
Fleet & Ramp Services	Ramp Service Trainer	5
Fleet & Ramp Services	Manager of Ground Operations	1
Fleet & Ramp Services	Administrative Assistant for Ground Operations	1
Fleet & Ramp Services	Supervisor, Ground Operations	14
Fleet & Ramp Services	Time Card Clerk	1
Fleet & Ramp Services	Modified Duty Coordinator for Ground Operations	1
Customer Services	Ticket Counter Agent	103
Customer Services	Concourse Agent	95
Customer Services	Baggage Agent	30
Customer Services	Specialty Areas Agent	10
Customer Services	Lead Ticket Counter Agent	4
Customer Services	Lead Concourse Agent	16
Customer Services	Lead Baggage Agent	5
Customer Services	Supervisor	5
Customer Services	Passenger Service Manager	1
Customer Services	Administrative Assistant, Customer Services	2
Customer Services	Customer Service Manager	1
Customer Services	Trainers, Customer Service	7
Reservations	Manager, Reservations	1
Reservations	Assistant Manager, Reservations	1
Reservations	Administrative Assistant, Reservations	1

Table 1 continued

Department	Job Title	# Workers
Reservations	Supervisor, Reservations	3
Reservations	Lead Reservation Agent	10
Reservations	Reservation Agent	172
Base Maintenance	Director of Base Maintenance	1
Base Maintenance	Manager, Base Maintenance	1
Base Maintenance	Manager, Shops	1
Base Maintenance	Manager, Engine Build Up	1
Base Maintenance	Maintenance Supervisor	10
Base Maintenance	Lead, C-Check	8
Base Maintenance	Lead, Sheet Metal	6
Base Maintenance	Lead, Shops	5
Base Maintenance	Administrative Assistant	1
Base Maintenance	Mechanic	300
Base Maintenance	Cleaner	4
Base Maintenance	Janitor	1

$$X_j = \frac{1}{S_j} \sum_{k=1}^{S_j} X_{jk} \,. \qquad (1)$$

The average exposure, X, for all workers can now be estimated using the formula

$$X = \frac{1}{W} \sum_{j=1}^{J} W_j X_j \,, \qquad (2)$$

where W is the total number of workers.

The quantity X is an estimate of the true population exposure and is, therefore, subject to sampling error. Assuming no correlation between the sampling errors of different job titles, the standard deviation (i.e., error in the estimate), σ_X, of X is

$$\sigma_X^2 = \frac{1}{W^2} \sum_{j=1}^{J} W_j^2 \sigma_{X_j}^2 , \tag{3}$$

where σ_{X_j} is the error of the estimate of exposure in the j^{th} job title. The estimated exposure for the j^{th} job title is given by Eq. (1), so $\sigma_{X_j}^2 = \sigma_j^2 / S_j$, where σ_j is the standard deviation of the exposure distribution for this job title. Placing this in Eq. (3) yields the expression

$$\sigma_X^2 = \frac{1}{W^2} \sum_{j=1}^{J} W_j^2 \sigma_j^2 / S_j . \tag{4}$$

The question we now address is how to select the sample sizes, S_j, to provide the most accurate estimate of the population exposure, that is, what values of S_j minimize the error, σ_X, in our estimate of the population exposure subject to the constraint that the total sample size must be equal to S. Using the methods of the calculus, it is not difficult to show that the optimum estimate of X is obtained when

$$S_j = S \frac{W_j \sigma_j}{W_1 \sigma_1 + W_2 \sigma_2 + \ldots + W_J \sigma_J} . \tag{5}$$

When the sample was drawn, we had no information about the values of σ_j. Consequently, for planning purposes, we assumed that $\sigma_1 \approx \sigma_2 \approx \ldots \approx \sigma_J$, in which case Eq. (5) becomes

$$S_j = \frac{W_j}{W} S . \tag{6}$$

Thus, the guideline we used for allocating our sample across job titles was that this allocation should be in proportion to the number of workers in each, that is a sampling probability proportional to size (PPS sample).

The first column of Table 2 lists the job titles that would have received at least 1 sample according to a PPS protocol. The second column lists the number of workers in job title that a PPS sample would have required. Note that 8 of the 15 job titles required only 1 sample. We decided that a sample of 1

Table 2. Number of workers sampled in selected job titles.

Job Title	Number of sampled workers		
	True PPS	Modified PPS	Actual
Mechanic	24	17	17
Ramp Service Agent	22	17	16
Reservation Agent	13	12	12
Ticket Counter Agent	8	7	7
Fleet Service Agent	8	7	7
Concourse Agent	7	7	7
Lead Ramp Service Agent	4	5	5
Baggage Agent	2	5	5
Lead Concourse Agent	1	4	4
Specialty Areas Agent	1	4	3
Maintenance Supervisor	1	3	3
Supervisor Ground Operations	1	3	3
Lead C-Check	1	3	3
Lead Reservation Agent	1	3	3
Lead Fleet Service Agent	1	3	2

would not be adequate to meaningfully characterize a job title, so we increased the sample sizes for these job titles to 3 or 4. In order to maintain a fixed total number of sample, the numbers of samples allocated to the job titles with the largest numbers of workers were correspondingly reduced. The third column in Table 2, labeled "Modified PPS," lists sample sizes after these changes. These sizes were the goals we attempted to obtain during the actual field work, described later in this report. Note that the 95% of the workers employed in the Ramp and Fleet Services, Customer Services, Reservations, and Maintenance Departments worked in the jobs included in our sample.

The duties of the individuals holding the job titles included in our sample are briefly described in the remainder of this section.

Ramp Service Agents–These employees work on and around the ramps where passengers en- and de-plane. The duties are principally handling baggage and freight.

Lead Ramp Service Agents–These individuals perform the same basic duties as Ramp Service Agents and, in addition, have the lead responsibility for a crew of ramp service agents assigned to service a particular incoming and/or outgoing flight.

Fleet Service Agent–These individuals work on and around the ramps where passengers en- and de-plane. Their duties include the cleaning and refurbishing of the interiors of airplanes, including kitchens and bathrooms, prior to passenger boarding.

Lead Fleet Service Agent–Similar duties of Fleet Service Agent, but includes responsibility for a crew.

Supervisor, Ground Operation–Administrative duties related to planning, oversight, and coordination of Ramp and Fleets Services personnel.

Ticket Counter Agents–The main duties of these individuals involve work at the ticket counters in airports, issuing tickets and checking baggage.

Concourse Agents–These individuals work at the concourse gates where passengers de- and en-plane. Their duties include passenger management and ticket collection.

Lead Concourse Agents–Oversight of concourse operations.

Baggage Agents–These individuals work in the baggage claim area, primarily dealing with missing and lost baggage.

Specialty Areas Agents–These agents perform tasks related to the oversight of cash drawers, certain accounting functions, and special projects that arise.

Reservations Agents–These individuals work in a large facility located about two miles south of the Seattle-Tacoma Airport. Their principal duties are telephone sales.

Lead Reservations Agents–Management of Reservations Agents.

Mechanics–These individuals perform maintenance on aircraft, including air frames, engines, electrical systems including avionics, and passenger accommodations. The job title mechanics also includes painters and sheet metal personnel.

Lead C-Check–Same work as mechanics but assumes a lead role for a crew.

Maintenance Supervisors–Management of maintenance activities including supervision of Lead C-Checks.

II.2. Magnetic-Field Measurements

Personal-exposure magnetic-field data (i.e., data obtained with a meter worn by a subject during their work shift) were obtained using Emdex II meters. The Electric and Magnetic Field Digital Exposure (Emdex) II meter was developed by Enertech Consultants in Campbell, CA. These battery powered meters are quite small ($16.8 \times 6.6 \times 3.9$ cm^3) and lightweight (about 330 grams). They can be programmed to repetitively sample the magnetic-field at selected time intervals and retain the resulting data in memory until the end of a data run. These data can be transferred to a personal computer (PC) for archival storage and later analysis.

A Emdex II meter contains three small coils that sense the magnetic field along the x, y and z axes. Normally, these three field values are aggregated into a single summary value known as the resultant field strength, B, defined as follows:

$$B = \sqrt{B_x^2 + B_y^2 + B_z^2} \ , \qquad (7)$$

where B_x, B_y, and B_z are the measured x, y and z magnetic-field components.

Emdex II meters are designed to cover the power-frequency range. The manufacturer's specified frequency bandwidth in the "broadband" mode is 40 to 800 Hz with a field-strength range of 0.1 to 3270 mG. These meters do record values for field components that fall outside of this frequency range, but with reduced sensitivity. For example, a 1 mG 1,000-Hz magnetic field will be measured as having a strength of about 0.6 mG.

Emdex II meters can also operate in a second mode, called the "harmonic" mode, where the unit's bandwidth is reduced to the range 100 Hz through 800 Hz. For the personal exposure measurements conducted in this study, Emdex II meters were programmed to take samples every 3 seconds in both broadband and harmonic modes.

Prior to the start of the study, all Emdex II meters were calibrated at a facility located in Richland WA. This facility uses a Helmholtz coil to produce highly uniform magnetic fields that are known to an accuracy of better than ± 2%. All meters used in this study were found to be within ±5% of their nominal calibration at 60 Hz.

Extensive experience with this type of meter has shown that they are reliable and stable. Nevertheless, to verify that they were operating properly, a secondary calibration was performed every day throughout the study. Meters were placed in a field of known strength in three different orientations to test each of the three internal field sensors. Readings at each of these orientations were recorded for all meters in calibration logs.

II.3. Measurement Protocol

Meters were distributed at pre-shift meetings to personnel who volunteered to participate. Meters were turned on, set to collect data every three seconds, and were placed in padded cases by the research staff before being given to the worker. Study participants were instructed to wear the meters at waist level and were asked to avoid tampering in any way with them. Workers were instructed to perform their duties normally. Participants were also asked to record their activities in a diary that was provided prior to giving out the meters. They were asked to record events and significant blocks of time. Diaries were kept so that we could determine what activity or activities was associated with a particular sequence of magnetic-field measurements. At the end of the work shift, meters and diaries were collected. Data collected from the meters was then downloaded to a PC.

Duplicate copies of all data files were made on two separate Zip disks. Along with the original copy of each data file that was maintained on the hard drive of the PC used in the field, we thus produced a total of three copies of each data file.

II.4. Data Analysis

Data collected during the study were converted to ASCII format using the software provided with the Emdex meters, and were imported into a commercial statistics package (STATA, Stata Corporation, College Station, TX). STATA was used to calculate 8 different statistics characterizing magnetic-field exposure. First, time-weighted-average (TWA) broadband and harmonic magnetic-field exposures were calculated by computing the average of all broadband and harmonic fields measured during each worker's work shift. The 90th percentile broadband exposures were determined by computing the 90th percentile of the set of broadband measurements contained in each worker's exposure recording. The numbers of broadband measurements in each recording that exceeded 2 mG, 5 mG, and 10 mG were then computed and used to determine the fractions of total measurements that exceeded these thresholds. Since magnetic-field measurements were taken at a uniform sampling rate throughout work shifts, these three statistics may be interpreted as the fractions of the total time during work shifts when broadband magnetic-field exposure exceeded thresholds of 2, 5, and 10 mG.

Finally, two statistics that characterize temporal broadband magnetic-field variability were calculated. The first metric we used was originally introduced by Wilson et al. (1996) and has come to be called the "Rate-of-Change" metric, abbreviated *RCM*. It is defined for a temporal sequence of regularly sampled broadband magnetic fields, B_1, B_2, ..., B_N, as follows:

$$RCM = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N-1}\left(B_{k+1} - B_k\right)^2} \ . \qquad (8)$$

Note that *RCM* has units of magnetic field strength (mG), which reflects the fact that its magnitude depends not only on the temporal structure of the magnetic field but also on its magnitude.

A second metric, denoted *RCM**, has recently been introduced to provide a more specific measure of temporal variability. This metric is simply the *RCM* metric defined by Equation (8) divided by the standard deviation of the broadband magnetic-field data in the time series under investigation. That is,

$$RCM^* = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N-1}\left(B_{k+1}-B_k\right)^2} \Bigg/ \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}\left(B_k-\overline{B}\right)^2}\,, \qquad (9)$$

where $\overline{B}$ is the mean of the sequence B_1, B_2, ..., B_N. The *RCM** metric is closely connected to the autocorrelation function for *B*. Indeed, when *N* is large, $RCM^* \approx \sqrt{2[1-A(\tau)]}$, where $A(\tau)$ is the autocorrelation function for the time lag, τ, between two consecutive samples (Yost, 1999).

The electrical systems in aircraft operate at a frequency of 400 Hz. This frequency is used, rather than the standard 60 Hz used for the generation and delivery of electric power in the U.S., because some electrical components (e.g., transformers) can be made smaller and lighter if they are operated at 400 Hz. Since some of the job titles include in our sample involve work around and inside aircraft, it is likely some of the exposure received by workers with these job titles derive from aircraft 400-Hz sources. A *pure* 400-Hz source can be distinguished from a 60-Hz source by comparing the harmonic and broadband amplitudes. If the source is 400 Hz, the harmonic and broadband amplitudes will be nearly equal, whereas if the source is purely 60 Hz, the harmonic amplitude will be nearly 0. (Most 60 Hz sources produce some harmonics at frequencies of 120 Hz, 180 Hz, and so forth, so the harmonic amplitude will usually not be 0 but will be small with respect to the broadband amplitude.) We examined this experimentally by computing the ratio of the harmonic to the broadband amplitude for every measurements in each sampled worker's exposure record; these ratios will be referred to as harmonic ratios in what follows.

III. RESULTS

III.1. Sampling Statistics

The column labeled "Modified PPS" in Table 2 lists the numbers of workers in each job title that we aimed to sample. While we achieved these goals in most cases, there were three instances where we did not. In one of these cases (Ramp Service Agent), the meter issued to one worker was inadvertently not turned on at the beginning of their shift, so no data were collected. In the second case (Specialty Area Agent), we were not able to obtain a fourth volunteer. In the final case (Lead Fleet Service Agent), one of our volunteers decided, after wearing their meter for about one hour, not to continue.

There were four instances where it was necessary to modify Emdex data files. Details are given in Table 3. In two cases, employees ended their work shifts sooner than expected and left their meters on their desks until they could be retrieved by our field personnel. In these cases, we estimated the lengths of times the meters had not been worn, from information provided by the employees and by inspection of the Emdex records, and deleted magnetic-field data acquired during these times. In another case, a worker stopped wearing their meter near the end of their shift complaining of discomfort. We deleted the latter part of this record. Finally, one worker took off their meter during their lunch period. Data obtained during this period was deleted from the record.

Table 3. Data files that required changes because of unusual circumstances.

Job Title	Problem	Solution
Lead Concourse Agent	Employee left work before meter could be retrieved	Delete data acquired after employee left
Concourse Agent	Removed meter during last hour of shift because of discomfort	Delete data acquired after employee stopped wearing meter
Lead Reservations Agent	Removed meter during lunch.	Mark portion of Emdex data record during lunch time invalid
Mechanic	Employee left work before meter could be retrieved	Delete data acquired after employee left

III.2. Distribution of Personal Exposures

The distribution of magnetic-field exposure data is invariably skewed, with most measurements falling at lower levels and only a relative few appearing at larger values. This pattern is illustrated in the left histogram in Figure 1, which contains the TWA personal exposures for all 97 workers monitored in the study. Note that most exposures fall below 2 mG, with a few at considerably larger levels, including one at 16.9 mG.

The right-hand histogram in Figure 1 shows the same data but log transformed. The data are much more nearly normal in distribution, but are still slightly skewed. Because they are more nearly log normal, we shall summarize them using both arithmetic and geometric statistics, with more emphasis placed on the latter than the former.

III.3. TWA Broadband and Harmonic Exposures

Figures 2 and 3 are modified box-and-whisker plots that summarize, respectively, the broadband (40-800 Hz) and harmonic (100-800 Hz) TWA personal exposures measured for each of the 15 job titles that were sampled in the study. The box for each job title extends vertically from the 25[th] percentile to the 75[th] percentile of the TWA broadband personal exposures measured for each job title. The horizontal line through the box marks the 50[th] percentile (i.e., the median). The whiskers extend vertically from the box to the 5[th] percentile

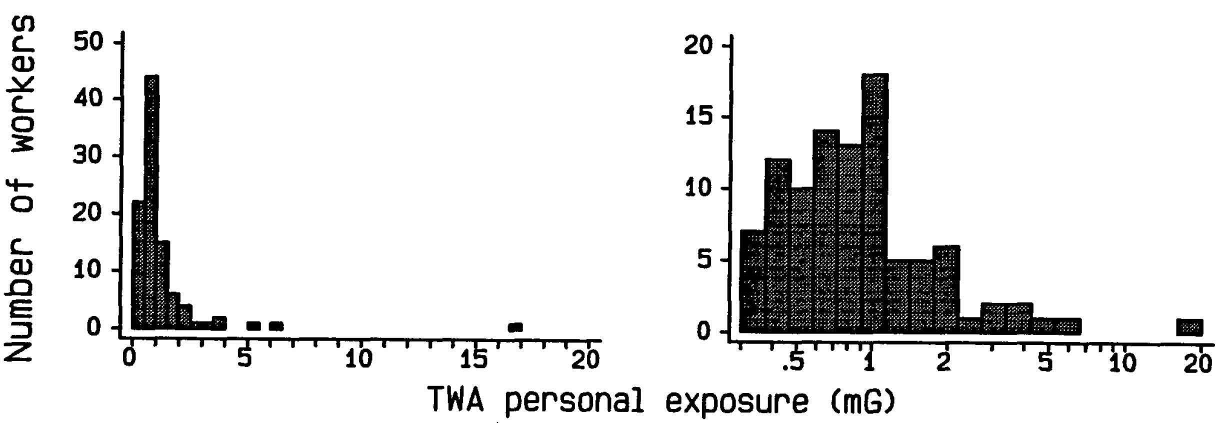

Figure 1. Histograms showing distributions of TWA broadband magnetic-field exposures.

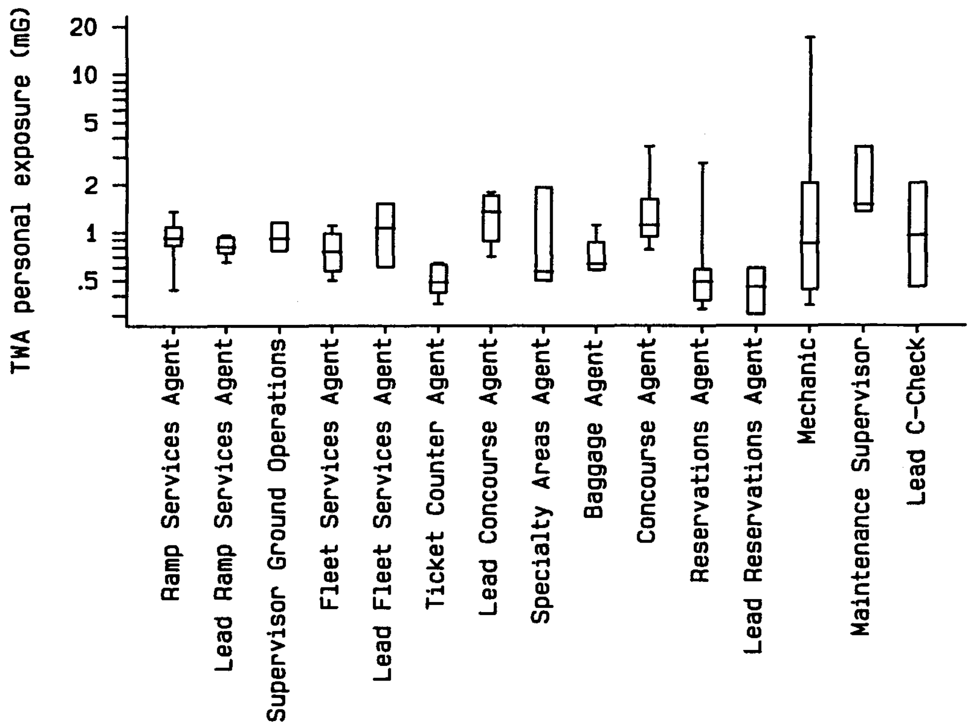

Figure 2. Modified box-and-whisker plot summarizing measured TWA broadband (40–800 Hz) personal exposures measured for 15 job titles.

(lower whisker) and the 95th percentile of the TWA personal exposures collected for the respective job title.

Summary statistics, including arithmetic and geometric means, are presented in Tables 4 and 5 for, respectively, TWA broadband and harmonic personal exposures measured for the workers sampled in each job title. There were significant differences in broadband TWA exposures between job titles [$p = 0.004$, Kruskal-Wallis test (Sokal and Rohlf, 1995)]. TWA harmonic exposures, on the other hand, did not differ across job titles ($p = 0.15$).

On average, the largest broadband TWA exposures were measured for Concourse Agents (geometric mean = 1.31 mG), Lead Concourse Agents (geometric mean = 1.22 mG), Mechanics (geometric mean of TWA exposures = 1.10 mG) and Maintenance Supervisors (geometric mean = 1.92 mG). Exposures did not differ among these four job titles ($p = 0.46$, Kruskal-Wallis test).

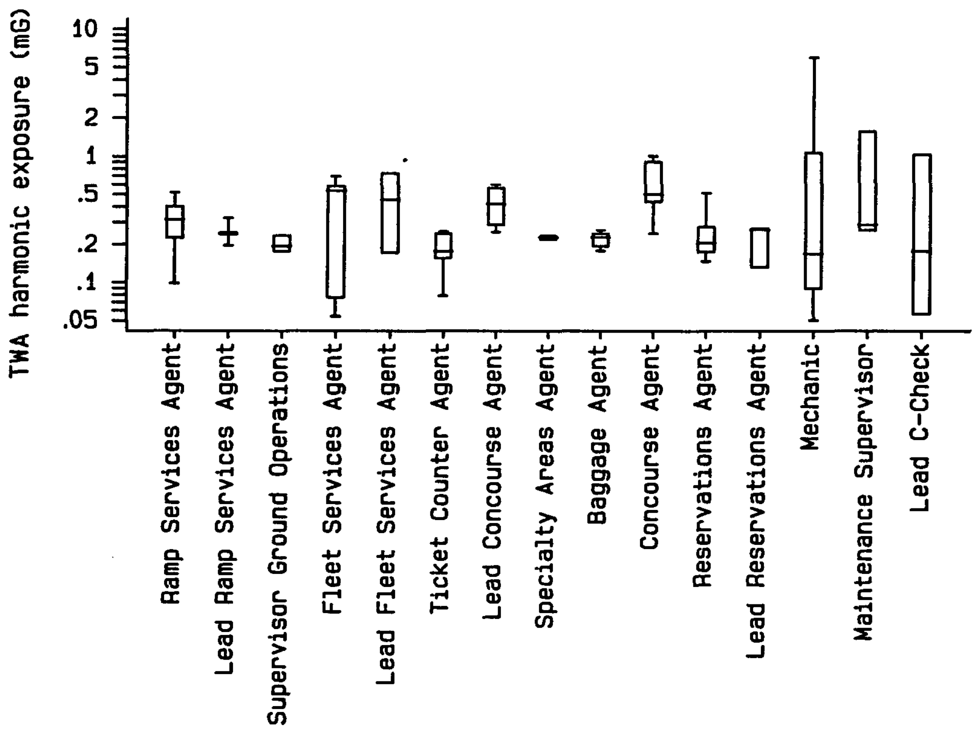

Figure 3. Modified box-and-whisker plot summarizing measured TWA harmonic (100–800 Hz) personal exposures measured for 15 job titles.

Table 4. Summary of TWA personal broadband (40–800 Hz) magnetic-field exposures of workers holding 15 job titles.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)	Geometric mean (mG)	Geometric S.D.
Ramp Service Agents	16	0.92	0.24	0.89	1.34
Lead Ramp Service Agents	5	0.82	0.13	0.81	1.17
Supervisors Ground Operations	3	0.95	0.20	0.93	1.23
Fleet Service Agents	7	0.78	0.22	0.75	1.33
Lead Fleet Service Agents	2	1.07	0.65	0.96	1.92
Ticket Counter Agents	7	0.50	0.11	0.49	1.24
Lead Concourse Agents	4	1.30	0.51	1.22	1.54
Specialty Areas Agents	3	1.00	0.80	0.82	2.11
Baggage Agents	5	0.76	0.23	0.73	1.34
Concourse Agents	7	1.49	0.95	1.31	1.65
Reservation Agents	12	0.78	0.78	0.59	1.98
Lead Reservation Agents	3	0.45	0.15	0.44	1.40
Mechanics	17	2.30	4.03	1.10	3.01
Maintenance Supervisors	3	2.12	1.21	1.92	1.69
Lead C-Check	3	1.15	0.82	0.96	2.13

Table 5. Summary of TWA personal harmonic (100–800 Hz) magnetic-field exposures of workers holding 15 job titles.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)	Geometric mean (mG)	Geometric S.D.
Ramp Service Agents	16	0.31	0.12	0.28	1.55
Lead Ramp Service Agents	5	0.25	0.05	0.25	1.20
Supervisors Ground Operations	3	0.20	0.03	0.20	1.16
Fleet Service Agents	7	0.42	0.25	0.30	2.92
Lead Fleet Service Agents	2	0.45	0.39	0.35	2.77
Ticket Counter Agents	7	0.18	0.06	0.17	1.48
Lead Concourse Agents	4	0.42	0.16	0.40	1.51
Specialty Areas Agents	3	0.23	0.01	0.23	1.03
Baggage Agents	5	0.22	0.03	0.22	1.17
Concourse Agents	7	0.58	0.27	0.53	1.61
Reservation Agents	12	0.24	0.11	0.23	1.46
Lead Reservation Agents	3	0.22	0.08	0.21	1.49
Mechanics	17	0.95	1.53	0.32	4.63
Maintenance Supervisors	3	0.70	0.74	0.48	2.74
Lead C-Check	3	0.42	0.53	0.22	4.31

All five jobs in the Fleet Services Department (the titles listed in the first five rows of Table 4) had geometric mean exposures of about 0.8–0.9 mG. There were no differences in exposure among these job titles (p = 0.62, Kruskal-Wallis test). In the Customer Services Department, ticket counter agents had the lowest broadband exposures (geometric mean = 0.49 mG), Specialty Areas Agents and Baggage Agents had exposures of 0.7–0.8 mG, and Concourse and Lead Concourse Agents had exposures of 1.2–1.3 mG. The exposures of the latter two job titles were significant larger than the other three job titles in the Customer Services Department (p = 0.0008, Kruskal-Wallis test). Broadband magnetic-field exposures in the Reservations Department were lower (geometric mean about 0.5 mG). Exposures in the Maintenance Department were somewhat larger.

A striking feature of the data summarized in Table 4 is the relatively small values of the geometric standard deviations (also, the arithmetic standard deviations). Residential magnetic fields typically have geometric standard deviations between 2.5 and 3.0 and arithmetic standard deviations similar in size to the arithmetic means. Thus, the geometric standard deviations for Ramp Services Agents (1.34), Lead Ramp Services Agents (1.17), Supervisors of Ground Operations (1.23), Fleet Service Agents (1.33), Ticket Counter Agents (1.24), and Baggage Agents (1.34) are striking, particularly in view of the fact that the minimum value of a geometric standard deviation, corresponding to an arithmetic standard deviation of 0, is 1. Evidently, magnetic fields in the airport environments where these groups ply their trades are unusually uniform.

The one exception to the pattern of reduced geometric standard deviations is Mechanics (Table 4). This can also be seen in Figure 2, where the 95th percentile TWA broadband magnetic-field exposure was much larger than for any other job title. Further examination showed that some of this increased variability was due to one worker, whose personal exposure was 16.9 mG. Removing this worker caused the geometric standard deviation for Mechanics to drop from the value of 3.01 listed in Table 4 to 2.40.

The harmonic magnetic fields summarized in Table 5 show few differences across job titles (p = 0.15, Kruskal-Wallis test). The largest harmonic exposure was measured for Concourse Agents (geometric mean = 0.53 mG). The harmonic data will be used later in this report to examine the frequency content of magnetic fields to which workers in various job titles were exposed.

III.4. Peak Personal Exposures

We next examined the exposure data to see which jobs were characterized by the largest peak exposures during work shifts. Remember that the exposure record for each worker consisted of a sequence of magnetic-field samples, taken every 3 s throughout work shifts. Starting from these data, we defined the following measures of peak exposure:

- 90^{th} percentile broadband exposure
- Fraction of broadband measurements > 2 mG
- Fraction of broadband measurements > 5 mG
- Fraction of broadband measurements > 10 mG

Figure 4 and Table 6 summarize the first measure of peak exposure, the 90^{th} percentile of the broadband magnetic-field exposure data collected during each work shift. Job title is a significant grouping variable ($p < 0.0023$, Kruskal-Wallis test). (That is, 90^{th} percentiles of worker exposure to magnetic fields are not the same for all job titles.) Jobs with geometric means of the 90^{th} percentiles > 2 mG are Lead Fleet Service Agents, Concourse Agents, Maintenance Supervisors, and Lead C-Checks.

Peak exposure was also characterized by calculating the fraction of broadband magnetic-field measurements in each worker's exposure record that exceeded threshold values of 2, 5, and 10 mG. Since the exposure data were taken at a constant sampling rate (measurement every 3 s) throughout work shift, this fraction can be interpreted as the fraction of time during a work shift that a worker's broadband magnetic-field exposure was greater than 2, 5, or 10 mG. Figures 5, 6, and 7 are modified box-and-whisker plots that summarize the fractions of time during work shifts that workers' exposures exceeded thresholds of 2, 5, and 10 mG, respectively. Tables 7, 8, and 9 provide arithmetic means and standard deviations summarizing these data. Workers whose exposures most often exceeded 2 mG during their work shifts included Concourse Agents, Reservation Agents, and Maintenance Supervisors. The broadband exposures of Concourse Agents, Lead Concourse Agents, and Maintenance Supervisors most often exceeded 5 mG during their work shifts. Using a 10-mG threshold, Mechanics stand out in Figure 7. As noted earlier, one mechanic had a TWA broadband magnetic-field exposure that was substantially elevated relative to the other workers holding this job title. Interestingly, this mechanic was not responsible for the elevated 95^{th} percentile shown in Figure 7.

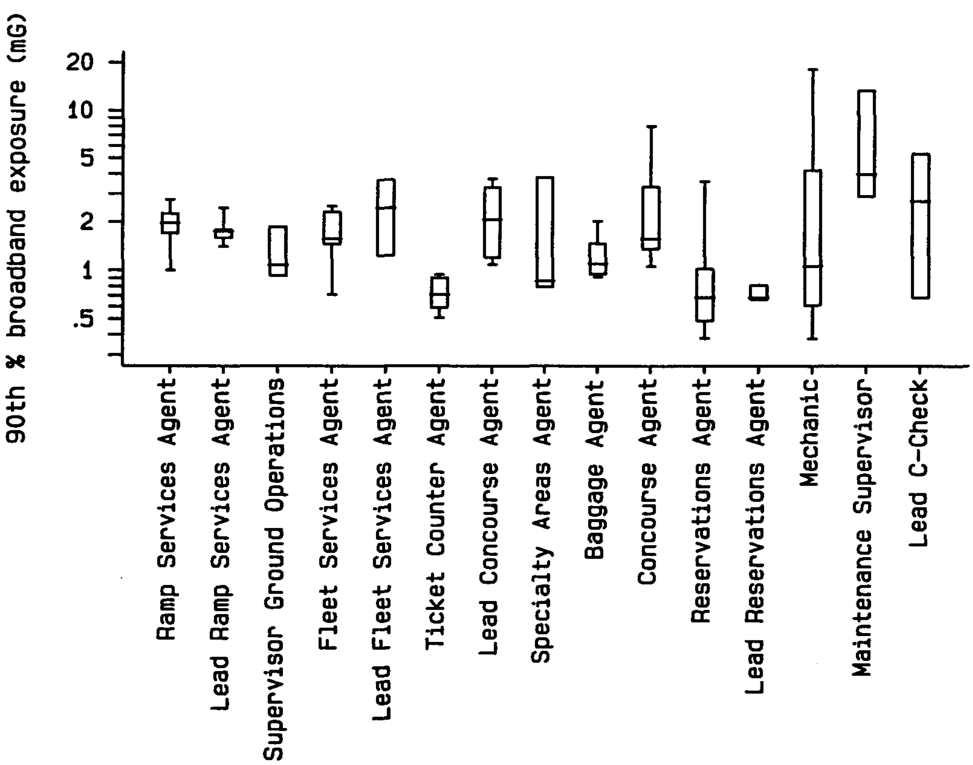

Figure 4. Modified box-and-whisker plot summarizing 90th percentile broadband (40–800 Hz) personal exposures measured for 15 job titles.

Table 6. Summary of 90th percentile broadband (40–800 Hz) magnetic-field exposures of workers holding 15 job titles.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)	Geometric mean (mG)	Geometric S.D.
Ramp Service Agents	16	1.98	0.45	1.92	1.28
Lead Ramp Service Agents	5	1.79	0.39	1.76	1.23
Supervisors Ground Operations	3	1.29	0.50	1.23	1.44
Fleet Service Agents	7	1.69	0.60	1.58	1.51
Lead Fleet Service Agents	2	2.45	1.72	2.13	2.15
Ticket Counter Agents	7	0.73	0.16	0.71	1.25
Lead Concourse Agents	4	2.24	1.26	1.98	1.80
Specialty Areas Agents	3	1.82	1.72	1.37	2.42
Baggage Agents	5	1.29	0.46	1.23	1.39
Concourse Agents	7	2.84	2.44	2.24	2.02
Reservation Agents	12	1.10	1.08	0.82	2.08
Lead Reservation Agents	3	0.72	0.08	0.71	1.12
Mechanics	17	3.86	5.25	1.75	3.53
Maintenance Supervisors	3	6.68	5.67	5.32	2.23
Lead C-Check	3	2.90	2.34	2.14	2.86

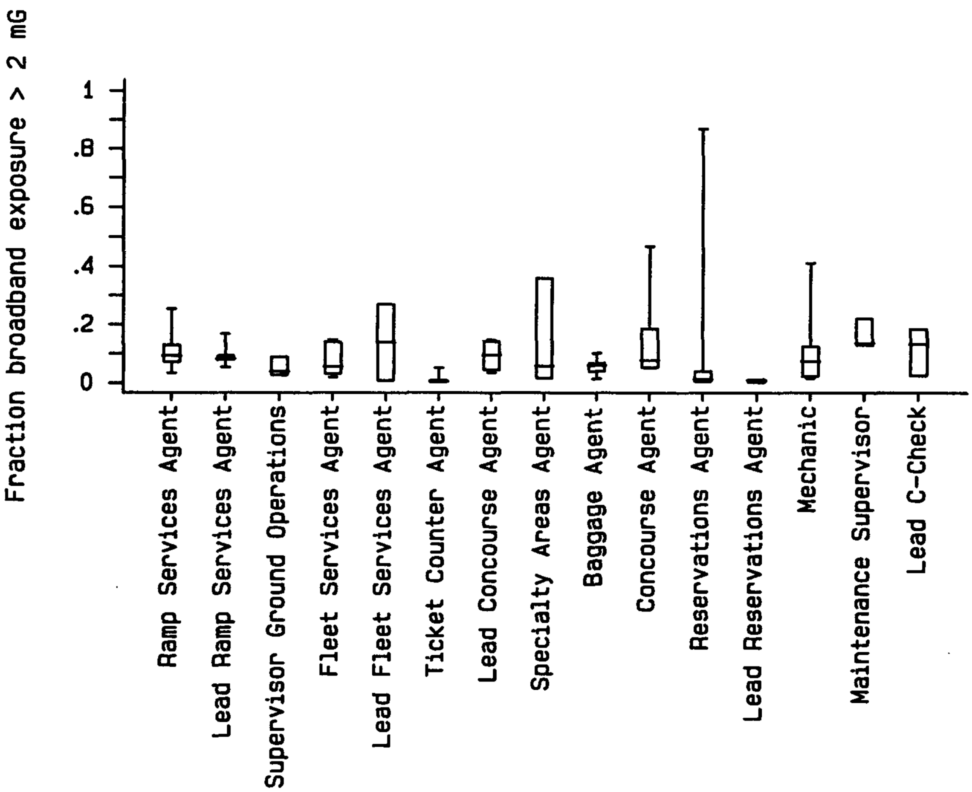

Figure 5. Modified box-and-whisker plot summarizing fractions of broadband (40–800 Hz) personal-exposure measurements > 2 mG

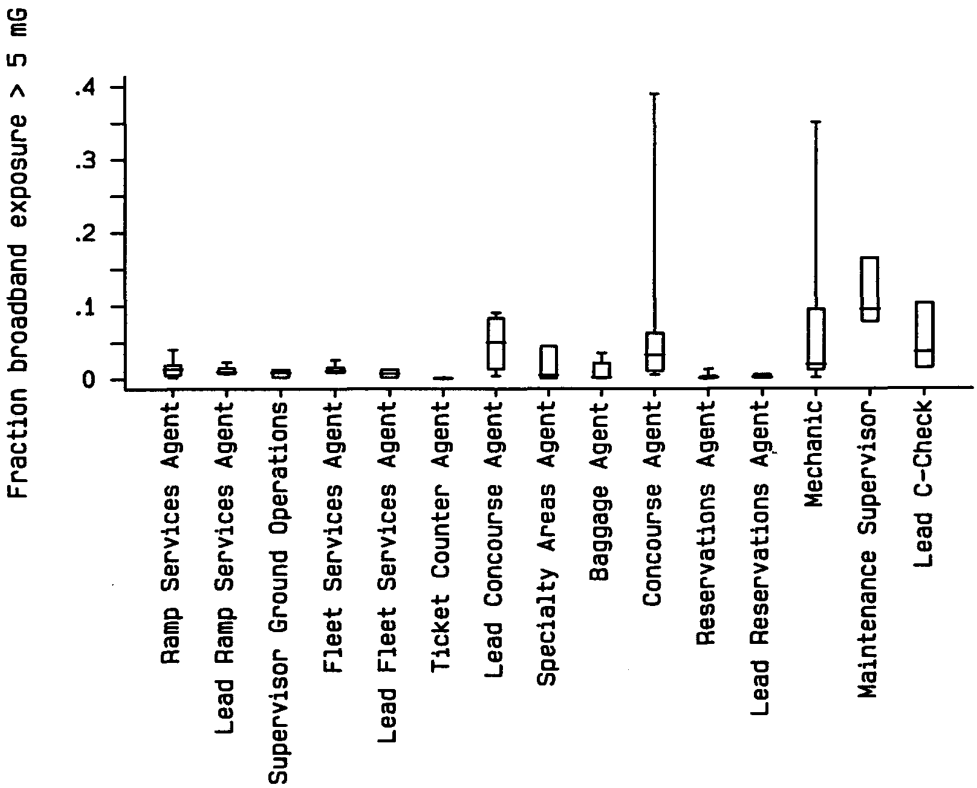

Figure 6. Modified box-and-whisker plot summarizing fractions of broadband (40–800 Hz) personal-exposure measurements > 5 mG

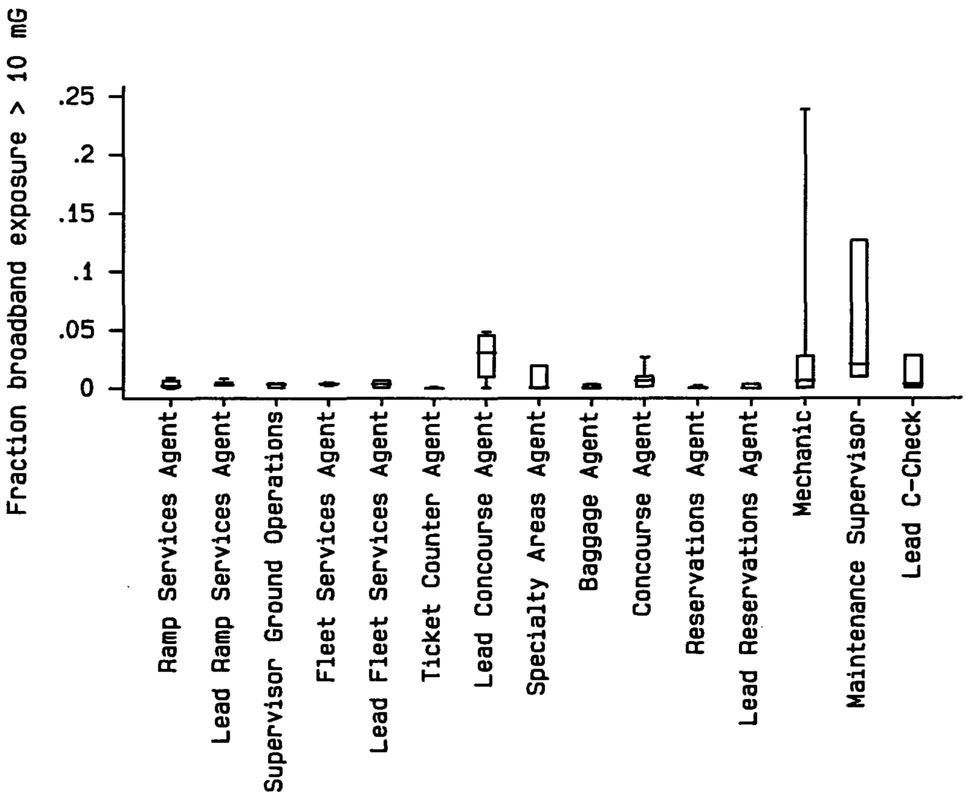

Figure 7. Modified box-and-whisker plot summarizing fractions of broadband (40–800 Hz) personal-exposure measurements > 10 mG

Table 7. Summary of fractions of time during work shift that broadband (40–800 Hz) magnetic-field exposures to workers holding 15 job titles were > 2 mG.

Job Title	N	Arithmetic mean	Arithmetic S.D.
Ramp Service Agents	16	0.11	0.06
Lead Ramp Service Agents	5	0.09	0.04
Supervisors Ground Operations	3	0.05	0.03
Fleet Service Agents	7	0.07	0.05
Lead Fleet Service Agents	2	0.14	0.18
Ticket Counter Agents	7	0.01	0.02
Lead Concourse Agents	4	0.09	0.06
Specialty Areas Agents	3	0.14	0.19
Baggage Agents	5	0.06	0.03
Concourse Agents	7	0.15	0.15
Reservation Agents	12	0.14	0.30
Lead Reservation Agents	3	0.01	0.00
Mechanics	17	0.11	0.13
Maintenance Supervisors	3	0.16	0.05
Lead C-Check	3	0.11	0.08

Table 8. Summary of fractions of time during work shift that broadband (40–800 Hz) magnetic-field exposures to workers holding 15 job titles were > 5 mG.

Job Title	N	Arithmetic mean	Arithmetic S.D.
Ramp Service Agents	16	0.014	0.010
Lead Ramp Service Agents	5	0.012	0.007
Supervisors Ground Operations	3	0.008	0.005
Fleet Service Agents	7	0.013	0.006
Lead Fleet Service Agents	2	0.007	0.008
Ticket Counter Agents	7	0.001	0.001
Lead Concourse Agents	4	0.049	0.041
Specialty Areas Agents	3	0.017	0.024
Baggage Agents	5	0.012	0.016
Concourse Agents	7	0.080	0.138
Reservation Agents	12	0.002	0.004
Lead Reservation Agents	3	0.002	0.002
Mechanics	17	0.071	0.100
Maintenance Supervisors	3	0.112	0.045
Lead C-Check	3	0.052	0.046

Table 9. Summary of fractions of time during work shift that broadband (40–800 Hz) magnetic-field exposures to workers holding 15 job titles were > 10 mG.

Job Title	N	Arithmetic mean	Arithmetic S.D.
Ramp Service Agents	16	0.004	0.003
Lead Ramp Service Agents	5	0.004	0.002
Supervisors Ground Operations	3	0.003	0.002
Fleet Service Agents	7	0.004	0.001
Lead Fleet Service Agents	2	0.004	0.004
Ticket Counter Agents	7	0.000	0.000
Lead Concourse Agents	4	0.027	0.022
Specialty Areas Agents	3	0.007	0.011
Baggage Agents	5	0.002	0.002
Concourse Agents	7	0.009	0.009
Reservation Agents	12	0.001	0.001
Lead Reservation Agents	3	0.001	0.002
Mechanics	17	0.038	0.068
Maintenance Supervisors	3	0.052	0.065
Lead C-Check	3	0.011	0.015

III.5. Exposures to 400-Hz Magnetic Fields

Since the electric power systems used on aircraft operate at 400 Hz, we expected that some job titles would include exposures at this frequency as well as to the 60-Hz magnetic fields that are produced by most electrically powered equipment. None of the measurements that we made provide direct information on frequency, but a comparison of the magnitudes of broadband and harmonic magnetic fields can provide an indication of whether 400-Hz magnetic fields were present. In this analysis, we will concentrate on the ratio, R, of the magnitudes of the harmonic field to the broadband field. Since the harmonic bandwidth extends from 100–800 Hz, we expect $R \approx 0$ for a pure 60-Hz magnetic field and $R \approx 1$ for a pure 400-Hz field. If both types of field are present in a particular environment, we expect R to be somewhere between 0 and 1.

The ratio, R, was calculated for every sequential measurement that comprised each worker's exposure record. We then constructed histograms that contained every measured value of R for each job title. The results are presented in Figure 8. Note that the vertical scale of each graph was normalized so that they all have the same vertical extent. The histograms for Ramp Service Agents, Lead Ramp Service Agents, Fleet Service Agents, Lead Fleet Service Agents, Mechanics, Maintenance Supervisors, and Lead C-Checks, all show peaks at $R = 1$, which we interpret as evidence for exposure to 400-Hz magnetic fields. These results seem reasonable since all of these jobs involve work near or in airplanes. The results in Figure 8 also indicate that exposure to 60-Hz magnetic fields occurs much more frequently in *all* jobs than exposure to 400-Hz fields.

III.6. Temporal Variability in Exposure

The most direct way to examine the temporal structure of the exposures received by the workers sampled in this study is to simply look at graphs of broadband exposure magnetic field strength versus time. Figure 9 shows four sample graphs. These graphs were selected to illustrate exposure records which exhibited relatively low temporal variability (Reservations Agent and Ticket Agent) and relatively large temporal variability (Concourse Agent and Ramp Services Agent).

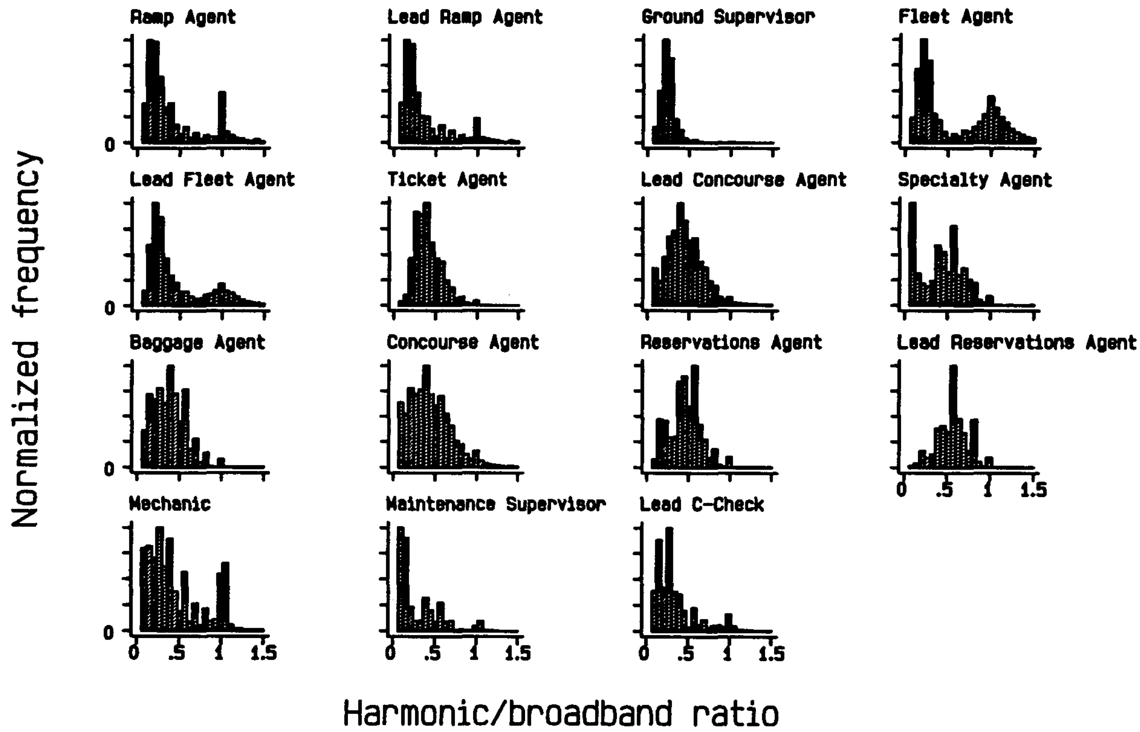

Figure 8. Histograms showing distribution of ratios of harmonic to broadband magnetic-field strengths.

Temporal variability can be quantitatively characterized using the *RCM* and *RCM** metrics defined earlier in this report. Figure 10 is a modified box-and-whisker plot that summarizes the corrected *RCM* data obtained to characterize the temporal variabilities of the exposures of the workers sampled in the study. Table 10 lists summary statistics for this metric. Job title is a statistically significant grouping factor for *RCM* ($p = 0.8 \times 10^{-5}$, Kruskal-Wallis test). Figure 10 and Table 10 show that there is substantial differences in *RCM* between job titles. *RCM* is larger for Fleet and Ramp Services personnel, larger for Customer Services' personnel who work in the concourse, larger for Maintenance personnel, and smaller for Customers' Services personnel who work at ticket counters and for Reservations personnel. Note that the arithmetic mean of *RCM* for mechanics is 9.4 mG, much larger than the geometric mean of 0.93 mG (Table 10). Figure 10 shows that at least one mechanic had very high values of *RCM*. In fact, examination of the data shows that this mechanic had *RCM* = 146 mG, whereas the next

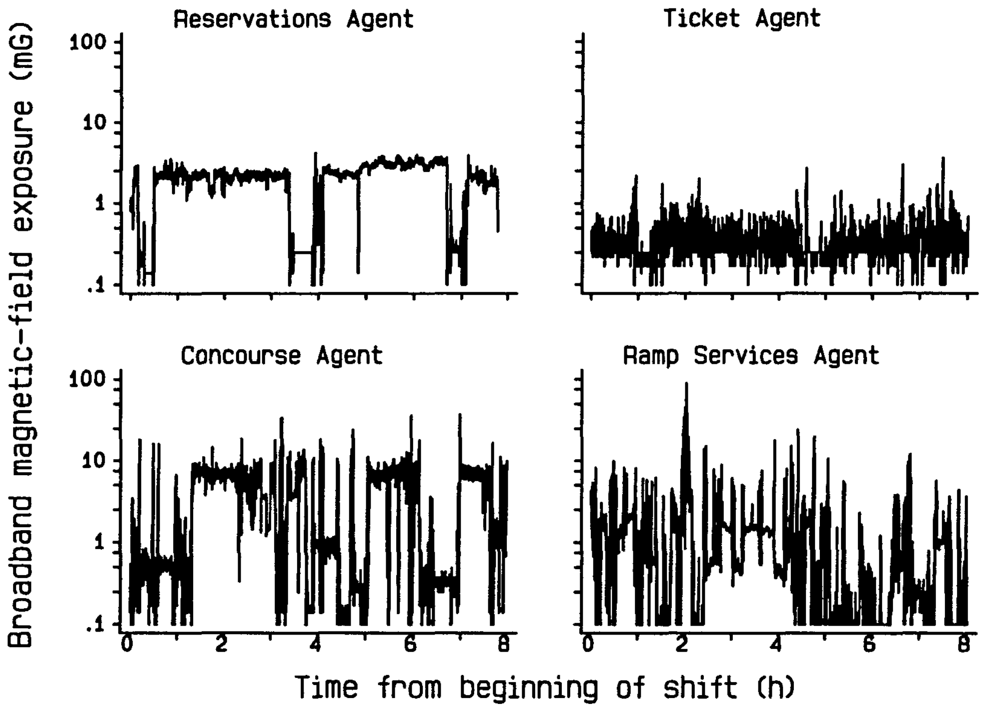

Figure 9. Exposure records of four workers selected to illustrate relatively low (upper two graphs) and relatively high levels of temporal variability.

highest mechanic had *RCM* = 3.5 mG. This was the same mechanic who had the largest TWA broadband magnetic-field exposure (Figure 2).

As noted earlier, *RCM* is not a pure measure of temporal variability because it depends not only on the amount of variability but also on the magnitudes of the fields under study. The modified *RCM* metric, *RCM**, was introduced to eliminate this "defect" in *RCM*. Figure 11 and Table 11 summarize *RCM** for the airline-workers data set. It is interesting that Mechanics do not stand out in this plot, as they did in the corresponding plot for *RCM* (Figure 10). Evidently, the value of *RCM* of 146 mG obtained for one mechanic was attributable to exposure to large magnetic fields rather than to large temporal variability.

Also of interest in Figure 11 and Table 11 is the fact that Reservation Agents are near the top of the distribution, whereas they were near the bottom when *RCM* was examined. Evidently,

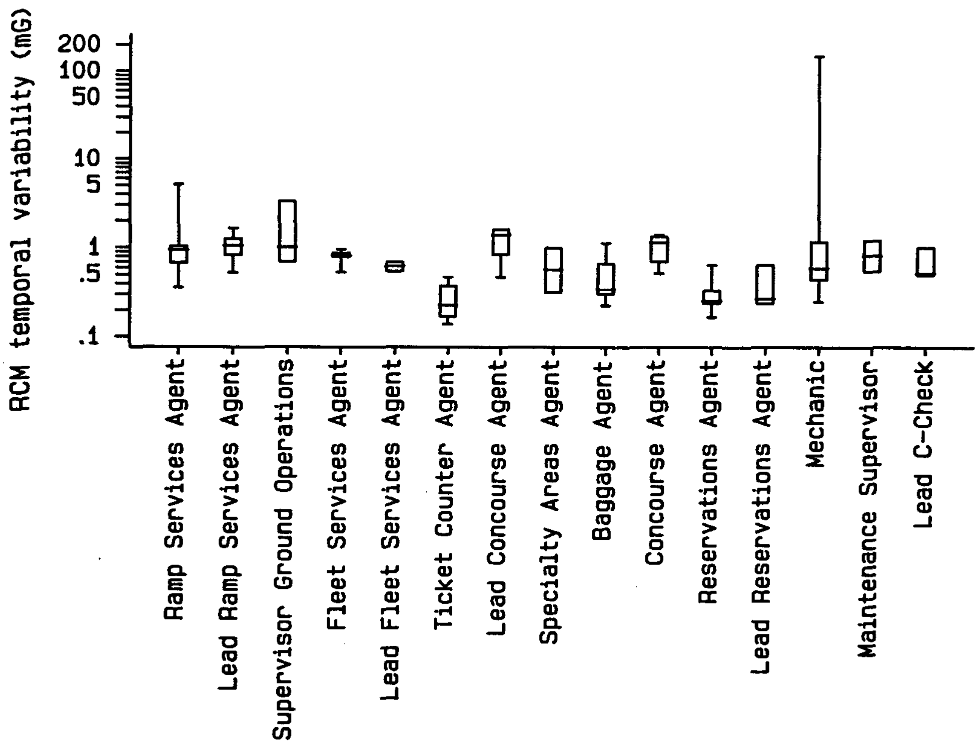

Figure 10. Modified box-and-whisker plot summarizing temporal variability of broadband magnetic-field exposures as gauged by the *RCM* metric.

Table 10. Summary of *RCM* metric characterizing temporal variabilities of broadband (40–800 Hz) magnetic-field exposures of workers holding 15 job titles.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)	Geometric mean (mG)	Geometric S.D.
Ramp Service Agents	16	1.17	1.09	0.95	1.78
Lead Ramp Service Agents	5	1.06	0.42	0.98	1.55
Supervisors Ground Operations	3	1.66	1.41	1.32	2.25
Fleet Service Agents	7	0.80	0.13	0.79	1.21
Lead Fleet Service Agents	2	0.61	0.10	0.61	1.18
Ticket Counter Agents	7	0.26	0.12	0.24	1.53
Lead Concourse Agents	4	1.21	0.52	1.09	1.78
Specialty Areas Agents	3	0.62	0.34	0.56	1.77
Baggage Agents	5	0.53	0.37	0.45	1.92
Concourse Agents	7	1.03	0.32	0.98	1.44
Reservation Agents	12	0.30	0.12	0.29	1.41
Lead Reservation Agents	3	0.38	0.22	0.34	1.71
Mechanics	17	9.43	35.21	0.93	4.37
Maintenance Supervisors	3	0.85	0.33	0.81	1.49
Lead C-Check	3	0.67	0.28	0.63	1.48

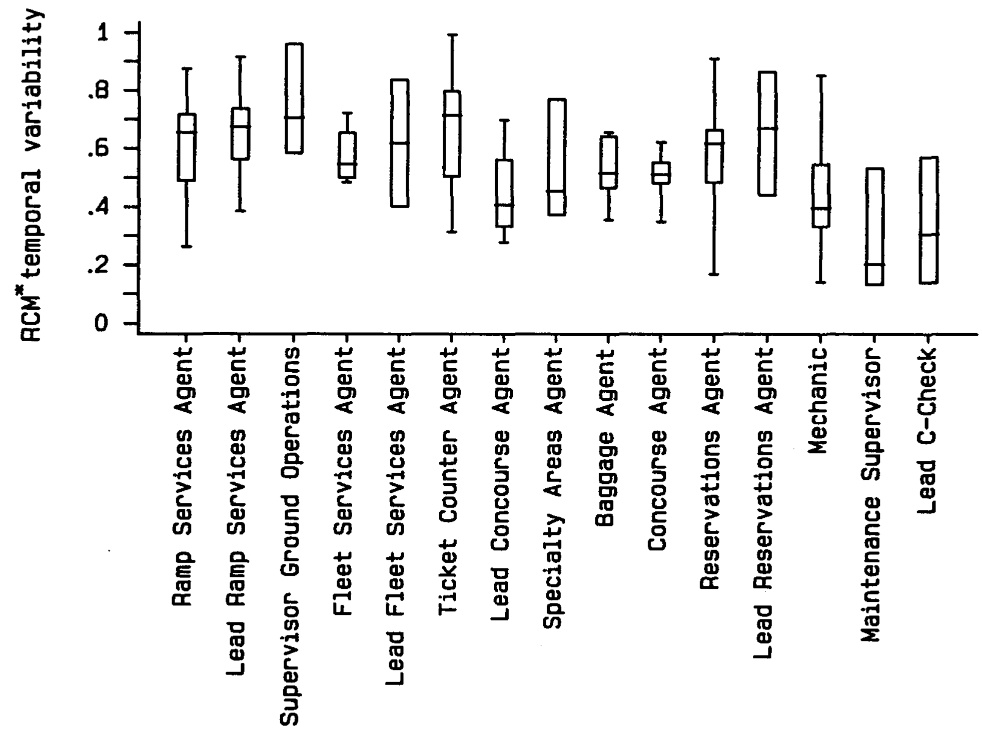

Figure 11. Modified box-and-whisker plot summarizing temporal variability of broadband magnetic-field exposures as gauged by the *RCM** metric.

Table 11. Summary of *RCM** metric characterizing temporal variabilities of broadband (40–800 Hz) magnetic-field exposures of workers holding 15 job titles.

Job Title	N	Arithmetic mean	Arithmetic S.D.	Geometric mean	Geometric S.D.
Ramp Service Agents	16	0.62	0.16	0.59	1.36
Lead Ramp Service Agents	5	0.66	0.20	0.63	1.38
Supervisors Ground Operations	3	0.75	0.19	0.74	1.28
Fleet Service Agents	7	0.58	0.09	0.57	1.15
Lead Fleet Service Agents	2	0.62	0.31	0.58	1.68
Ticket Counter Agents	7	0.69	0.22	0.65	1.46
Lead Concourse Agents	4	0.45	0.18	0.42	1.46
Specialty Areas Agents	3	0.53	0.21	0.51	1.45
Baggage Agents	5	0.53	0.13	0.51	1.29
Concourse Agents	7	0.51	0.08	0.50	1.20
Reservation Agents	12	0.58	0.21	0.53	1.62
Lead Reservation Agents	3	0.66	0.21	0.63	1.41
Mechanics	17	0.44	0.18	0.41	1.61
Maintenance Supervisors	3	0.29	0.21	0.24	2.04
Lead C-Check	3	0.34	0.22	0.29	2.03

Reservation Agents experience a relatively small but more temporally variable magnetic field than do many of the other job titles examined in this study.

III.7. Relation Between Exposure Metrics

We have examined the following measures of magnetic-field exposure in this report:

1) TWA broadband personal exposure
2) TWA harmonic personal exposure
3) 90^{th} percentile broadband personal exposure
4) Fraction of time during work shift when broadband magnetic field > 2 mG
5) Fraction of time during work shift when broadband magnetic field > 5 mG
6) Fraction of time during work shift when broadband magnetic field > 10 mG
7) *RCM* temporal variability metric
8) *RCM** temporal variability metric

The purpose of this section is to examine correlations between these alternative methods of characterizing occupational magnetic-field exposure. Table 12 lists Spearman correlation coefficients between various pairs of these metrics.

Table 12 shows that there is a fairly high degree of correlation between many of the metrics used in this study, indicating that they do not all provide independent information about exposure. As far as the author knows, there is no consensus as to the level of correlation between two measures of exposure required to conclude that they are not independent. Thus, the data were examined assuming that a "threshold" level of correlation of 0.90, 0.80, and 0.70 was required to designate two exposures measures as dependent. We then discarded one of each pair of dependent measures. The results of this process are presented in Table 13.

If a threshold correlation of 0.90 is assumed, all of the metrics considered in this report are independent except for the 90^{th} percentile broadband magnetic-field strength, which is strongly correlated (coefficient = 0.93) with the fraction of time during exposure the broadband magnetic field exceeded 2 mG. If the threshold level is reduced to 0.80, two additional metrics can be removed because they are dependent on others: The fractions of time during exposure that the broadband magnetic field exceeded 2 mG and 10 mG. Finally, if the threshold correlation is reduced to 0.70, the list of independent metrics includes only the TWA broadband magnetic field and the two rate-of-change metrics, *RCM*, and *RCM**.

Table 12. Spearman correlation coefficients between eight exposure metrics used to describe occupational magnetic-field exposures received by 97 employees employed by a major airline company.

	TWA broadband	TWA harmonic	90th % broadband	Fraction > 2 mG[a]	Fraction > 5 mG[a]	Fraction > 10 mG[a]	RCM[a]
TWA harmonic	0.78[b]						
90th % broadband	0.87[b]	0.66[b]					
Fraction > 2 mG[a]	0.84[b]	0.64[b]	0.93[b]				
Fraction > 5 mG[a]	0.71[b]	0.53[b]	0.70[b]	0.72[b]			
Fraction > 10 mG[a]	0.70[b]	0.60[b]	0.62[b]	0.61[b]	0.86[b]		
RCM[a]	0.67[b]	0.54[b]	0.57[b]	0.56[b]	0.71[b]	0.84[b]	
(*RCM**)[a]	-0.47[b]	-0.36[c]	-0.47[b]	-0.55[b]	-0.52[b]	-0.36[c]	-0.05

[a]Broadband [b]$p < 0.0001$ [c]$p < 0.001$

Table 13. List of "independent" exposure metrics assuming two metrics are dependent if the Spearman correlation between them exceeds threshold levels of 0.9, 0.8, or 0.7

Threshold correlation	Independent exposure measures
0.90	TWA broadband magnetic field
	TWA harmonic magnetic field
	Fraction of time broadband field > 2 mG
	Fraction of time broadband field > 5 mG
	Fraction of time broadband field > 10 mG
	RCM
	*RCM**
0.80	TWA broadband magnetic field
	TWA harmonic magnetic field
	Fraction of time broadband field > 5 mG
	RCM
	*RCM**
0.70	TWA broadband magnetic field
	RCM
	*RCM**

Another interesting result in Table 12 is the negative correlation between the modified rate-of-change metric, *RCM**, and all other metrics included in this study. The relation between *RCM** and the TWA broadband magnetic field is shown in Figure 12. The figure shows clearly that subjects with exposures to stronger magnetic fields experience less magnetic-field variability as gauged by the *RCM** metric.

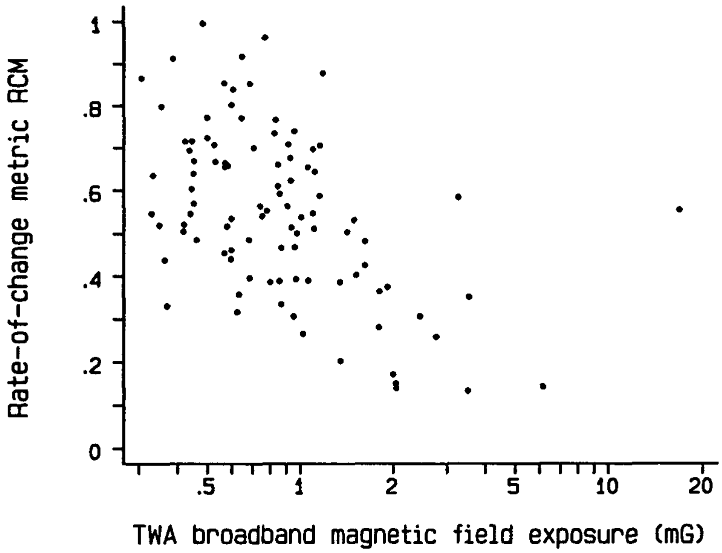

Figure 12. Scatter plot showing relation between TWA broadband magnetic-field exposure and the modified rate-of-change metric, *RCM*.

III.8. Estimate of Company-Wide Average Exposure

We now use our data to approximately characterize the entire workforce employed in the Ramp and Fleet Services, Customer Services, Reservations, and Maintenance Groups at this airline. Suppose that the j^{th} job title is held by W_j workers and that we sampled S_j of these workers. Starting with the sampled data set, we should weight each sample by the factor W_j/S_j in order to reconstruct from the sample to complete data set. We accomplished this by replacing each observation in the data set with W_j/S_j copies of itself. (Actually, to minimize the effects of rounding W_j/S_j to the nearest integer value, we replaced each sampled value with $100W_j/S_j$ copies of itself, resulting in a data set with 125,297 observations.) The resulting data set was used to calculation statistics characterizing the complete population of airline workers. The results are given in Table 14.

Table 14. Statistics summarizing magnetic-field exposures for population of airline workers employed in Ramp and Fleet Services, Customer Services, Reservations, and Maintenance.

Exposure metric	Population statistics			
	Arithmetic mean	Arithmetic SD	Geometric mean	Geometric SD
TWA broadband personal exposure	1.24 mG	2.06 mG	0.85 mG	2.00
TWA harmonic personal exposure	0.47 mG	0.79 mG	0.28 mG	2.44
90^{th} percentile personal exposure	2.3 mG	2.89 mG	1.51 mG	2.26
Fraction of time exposure > 2 mG	0.10	0.14	0.049	3.94
Fraction of time exposure > 5 mG	0.031	0.067	0.0086	5.41
Fraction of time exposure > 10 mG	0.012	0.036	0.0026	5.92
Temporal variability *RCM* metric	2.9 mG	17 mG	0.68 mG	2.60
Temporal variability *RCM** metric	0.56	0.19	0.52	1.50

IV. SUMMARY AND CONCLUSIONS

IV.1. Summary

This study characterized the occupational exposures to magnetic fields of non-flying workers employed by a major airline company. The first step of the project was to generate a list of job titles and the numbers of workers holding each (Table 1). From this list, a sampling plan was developed that tended to select job titles for sampling in proportion to the numbers of workers holding each. In the end, 15 job titles were sampled (Table 2).

Volunteer workers were asked to wear Emdex II magnetic-field meters at a waist location for one work shift. These meters were set to record the broadband (40–800 Hz) and harmonic (100–800 Hz) magnetic fields sampled every 3 s. From the resulting data the following eight exposure metrics were calculated:

1) Time-weighted-average broadband personal magnetic-field exposure
2) Time-weighted-average harmonic personal magnetic-field exposure
3) 90^{th} percentile broadband personal magnetic-field exposure
4) Fraction of time during work shift when broadband exposure > 2 mG
5) Fraction of time during work shift when broadband exposure > 5 mG
6) Fraction of time during work shift when broadband exposure > 10 mG
7) Temporal broadband magnetic-field variability using the *RCM* metric
8) Temporal broadband magnetic-field variability using the *RCM** metric

Most of these quantities were more nearly log normally than normally distributed (Figure 1).

The geometric means of the time-weighted-average (TWA) broadband magnetic-field exposures varied from a minimum of 0.44 mG for Lead Reservations Agents to a maximum of 1.92 mG for Maintenance Supervisors. Other job titles with TWA broadband exposures above 1 mG were Concourse Agents (1.31 mG), Lead Concourse Agents (1.22 mG), and Mechanics (1.10 mG).

It is interesting that both of the jobs that involve work in the concourse area of the Seattle-Tacoma Airport had relatively high exposures, exposures that were more uniform than in many occupational environment.

The geometric mean of the TWA harmonic magnetic-field exposure varied from 0.17 mG for Ticket Counter Agents to 0.53 mG for Concourse Agents (Table 5).

Four different metrics were used to capture peak magnetic-field exposure (Tables 6–9). The geometric means of the 90^{th} percentile exposure ranged from 0.71 mG for Ticket Counter Agents and Lead Reservation Agents to 5.32 mG for Maintenance Supervisors. The fraction of time during work shifts that broadband magnetic-field exposure exceeded 2 mG varied from 0.01 for Ticket Counter Agents and Lead Reservation Agents to 0.16 for Maintenance Supervisors. The pattern of exposure was similar when the fractions of measurements > 5 mG and > 10 mG were used as a metric, except all jobs were characterized by progressively smaller values.

Jobs that involved work inside or near airplanes conveyed some exposure to 400-Hz magnetic fields. These jobs included Ramp Agents, Lead Ramp Agents, Fleet Agents, Lead Fleet Agents, Mechanics, and Maintenance Supervisors.

Temporal variability of the broadband exposure magnetic field was assessed using two metrics, the so-called *RCM* and *RCM** metrics. The first is sensitive to both the temporal structure of the field, expressed as a percentage of the average field strength, and the size of the field. The second metric (*RCM**), on the other hand, depends only on the temporal structure of the magnetic field under study (again expressed as a percentage of the average field strength). The *RCM* metric varied from 0.24 mG for Ticket Counter Agents to 1.32 mG for Supervisors of Ground Operations. There was little relation between the *RCM* and *RCM** values for job titles. For example, the two largest values of *RCM** corresponded to the two job titles with the largest (Supervisors of Ground Operations) and smallest (Lead Reservations Agents) values of *RCM*.

Investigation of the Spearman correlations between exposure as measured with the various metrics used in this study showed that most were fairly closely related. By discarding metrics whose correlations with other metrics was greater than 0.70, a minimal list of reasonably independent metrics was formed that contained just three: TWA broadband personal exposure, *RCM*, and *RCM**.

As noted at several points in the preceding section, there was one mechanic whose TWA broadband exposure (16.9 mG) and *RCM* (146 mG) were markedly larger than the corresponding values for the other employees included in our survey. The recording for this employee is shown in Figure 13. Except for three brief episodes, this mechanic was exposed to quite small fields. During these episodes, however, the broadband field exceeded 1,000 mG. Examination of our records shows that this particular mechanic was involved with the nondestructive testing using magnetic techniques.

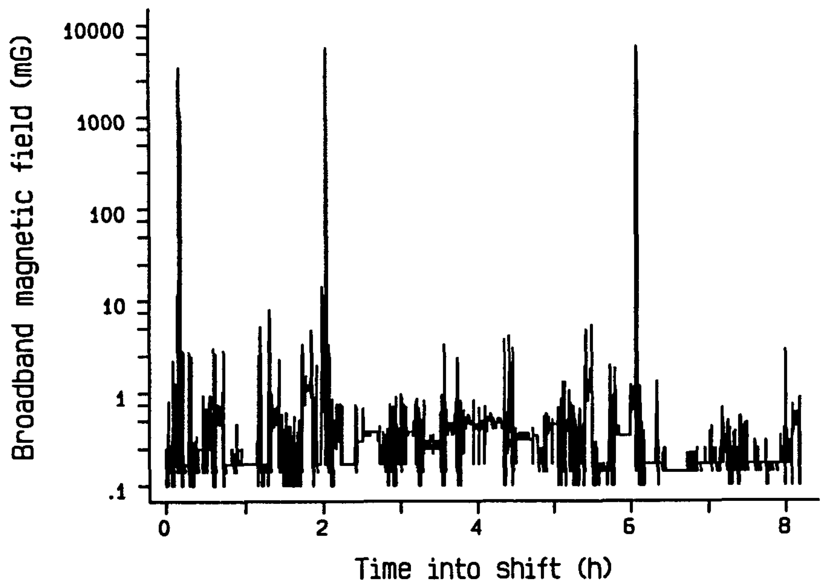

Figure 13. Measured broadband magnetic-field personal exposure of one mechanic.

IV.2. Accuracy of Results

Extensive experience has shown that magnetic-field data acquired using Emdex II meters, such as that presented in this report, are consistently accurate. We checked the performance of these meters regularly throughout the course of the field work and found no problems with any of them.

In a field study involving personal exposure measurements, one is always dependent on the cooperation of the subjects. Since we had as many as 11 meters deployed at any one time, it was not possible to directly observe that subjects were always following the protocol. Our belief from talking to subjects when the meters were collected is that the level of protocol adherence was high.

As discussed earlier, we had reason to expect that the frequency spectra of the magnetic fields we measured were dominated by 60 Hz, some harmonics of 60 Hz, 400 Hz, and harmonics of 400 Hz. The bandwidth of an Emdex II (40–800 Hz) is sufficient to encompass all but the harmonics of 400 Hz. Denote by B_{400}, B_{800}, B_{1200}, ... the magnitudes of a 400-Hz magnetic field and its second, third, fourth, ... harmonics. Then the rms field strength, B_{rms}, of the field is

$$B = \sqrt{B_{400}^2 + B_{800}^2 + B_{1200}^2 + \cdots} \quad (10)$$

An Emdex II meter will respond fully to B_{400}, but only partially to B_{800}, B_{1200}, ... It can be shown that for most distorted types of waveforms, B will be equal to B_{400} within a few percent. For example, if the waveform was triangular shaped rather than sinusoidal, the percentage error in the determination of B that one would make by discarding all harmonics would be 0.7% (CRC, 1978). Thus, we expect that errors due to the limited bandwidth of the Emdex II meters used in this study will be quite small.

IV.3. Final Conclusions.

The average TWA broadband personal exposure to magnetic fields for non-flying workers employed in a major airline company is 1.24 mG (Table 14), a value which is only slightly elevated relative to the typical U.S. residence (Zaffanella, 1993). Based on our measurements, the estimated numbers of the 1315 employees in the Ramp & Fleet Services, Customer Services, Reservations, and Base Maintenance groups that have TWA broadband occupational personal exposures > 2 mG and > 5 mG are about 143 and 37, respectively. (These estimates were obtained from the data set described in Section III.8.) These numbers are clearly insufficient to support an epidemiological study with the goal of detecting associations between TWA broadband exposure and human disease.

The average TWA harmonic personal exposure to magnetic fields of Alaska Airlines employees is 0.47 mG, a value that is about 3 times typical residential ambient levels (Zaffanella, 1993). Insufficient residential data are available to enable us to compare any of the other exposure metrics in Table 14 to typical residential levels, but it seems possible that some of them, such as the two rate-of-change metrics, might also be elevated.

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